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G-CLASS: geosynchronous radar for water cycle science – orbit selection and system design

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Abstract: The mission geosynchronous – continental land atmosphere sensing system (G-CLASS) is designed to study the diurnal water cycle, using geosynchronous radar. Although the water cycle is vital to human society, processes on timescales less than a day are very poorly observed from space. G-CLASS, using C-band geosynchronous radar, could transform this. Its science objectives address intense storms and high resolution weather prediction, and significant diurnal processes such as snow melt and soil moisture change, with societal impacts including agriculture, water resource management, flooding, and landslides. Secondary objectives relate to ground motion observations for earthquake, volcano, and subsidence monitoring. The orbit chosen for G-CLASS is designed to avoid the geosynchronous protected region and enables integration times of minutes to an hour to achieve resolutions down to ∼20 m. Geosynchronous orbit (GEO) enables high temporal resolution imaging (up to several images per hour), rapid response, and very flexible imaging modes which can provide much improved coverage at low latitudes. The G-CLASS system design is based on a standard small geosynchronous satellite and meets the requirements of ESA's Earth Explorer 10 call.

1 Introduction

Geosynchronous – continental land-atmosphere sensing system (G-CLASS) is a mission proposal for the European Space Agency call for its Earth Explorer 10 mission. It is a geosynchronous radar mission designed to address key measurement needs of Earth scientists studying aspects of the water cycle. The particular strength of satellites in geosynchronous orbit (GEO) is their ability to observe continental regions practically continuously. Radar is sensitive to backscatter of Earth's surface and also the refractive index of the atmosphere: GEO radar can, therefore, in principle provide almost continuous monitoring of Earth's surface and atmosphere.

1.1 Geosynchronous radar

Researchers have been interested in GEO radar since the 1970s. Early work in the US [1] concerned high inclination orbits (∼60°) and required high power and huge antennas. Since then, groups in Europe [2, 3] and China [4] have picked up the ideas and developed a broad range of mission concepts – but still motivated by the ability of GEO radar to provide high temporal resolution, with powerful and flexible imaging modes.

1.2 System design of geosynchronous radar

Radar missions are challenging to design since so many system parameters are interconnected. Some of the key system design choices are:

- User requirements: high spatial resolution is demanding, but all the usual radar image parameters (backscatter, interferometric phase and coherence, and polarimetry) are in principle available,
- Waveband: low Earth orbit radars for surface studies range from P-band (Biomass) up to X-band (e.g. TerraSAR-X),
- Orbit (inclination in particular): high inclination orbits tend to imply high speeds for the satellite relative to Earth.

Once these features have been defined, the detailed system can be developed. Hobbs *et al.* [5] discuss a number of the key relationships and constraints.

1.3 Water cycle science requirements

Earth's water cycle is fundamental to life and to human society. It has, therefore, been the subject of much research. However, there are aspects which are still poorly understood and to which space mission could contribute usefully. One of these is to improve understanding of rapid, fine-scale processes, in particular those on scales of hours or faster and 20 to 10 km. Trenberth and Asrar [6] discuss this need, and specific research questions include:

- What processes control intense storms which cause local flooding, landslides etc?
- How can high-resolution numerical weather prediction (NWP) models be validated and initialised?
- What are the diurnal changes in snow water content which control run-off from mountain areas?
- How does soil moisture vary during the day, especially in hot, dry regions?

These questions define a coherent set of science objectives around which the G-CLASS mission has been defined. The particular measurement requirements are expressed in community-defined databases such as the World Meteorological Organisation's Observing Systems Capability Analysis and Review tool (WMO OSCAR) [7]. This science defines science objectives SO1 and SO2 (Table 1). Without any further measurements, an additional objective related to solid Earth science can also be addressed: SO3 related to ground surface motion.

Table 2 lists the specific measurement requirement related to each of the science objectives (note that all data required for SO3 are already provided for SO1 or SO2).

For a geosynchronous radar, the raw data are the single-look complex radar images at ‘coarse’ resolution of 0.5–1 km available every 10–15 min. These are used to estimate the atmospheric phase screen (APS, from the phase change since previous images). Since the APS values change with time, this derived phase is used to correct for changes in atmospheric refractive index (due to changes in humidity etc.) so that long-integration-time synthetic apertures can be created to focus the high spatial resolution images.

1.4 Top-level system design

The temporal resolution can be met with either a large constellation of low Earth orbit satellites or with a GEO satellite. For access over continental areas (but not global coverage), a GEO satellite is lower cost and has great flexibility to provide images as and when required. Microwave radars are sensitive to water both on Earth's surface and in its atmosphere, and thus a GEO radar may in principle provide the required observations (Table 2).

The radar band is an important choice. For G-CLASS, a C-band radar is proposed since this is sensitive to both the atmospheric humidity and surface moisture, but is not too sensitive to ionospheric electron content. C-band also achieves good coherence over most surface types of interest: this is needed to allow interferometry. Alternative bands with similar features are S- and L-bands, but these longer wavelength bands are more sensitive to the ionosphere and tend to require larger (and thus more expensive and massive) antennas.

2 Orbit selection

Having chosen a C-band radar in GEO defines only the top-level system design. The next important decision is the orbit. A range of orbits have been proposed for GEO radars, from quasi-geostationary orbits (QGS) [8] to ones with inclination up to 60° [1]: higher inclinations tend to mean higher speeds relative to Earth.

As the relative speed increases, the integration time taken to form a sufficiently long synthetic aperture reduces, and so to maintain a satisfactory signal-to-noise ratio (SNR), the transmitted power and/or the antenna area must increase. For high inclination orbits (30° or more), the relative speed is $\geq 1\ \mathrm{km\ s^{-1}}$ and very large antennas (~20 m or more diameter) are typically assumed. At the other extreme, the QGS orbits are designed to stay within the geostationary box of ±0.1° longitude and have relative orbit speeds of only a few $\mathrm{m\ s^{-1}}$, leading to integration times of several hours for spatial resolution below 100 m.

A compromise between GSO and high inclination is proposed for G-CLASS to achieve fine resolution within about an hour without needing huge antennas. The relative orbit speed is ∼20 $\mathrm{ms^{-1}}$, but without careful orbit design this could create a collision risk with commercial geostationary communication satellites (COMSATs). The G-CLASS orbit is, therefore, designed to remain away from the geostationary ring where COMSATs operate. A protected GEO region is defined within 200 km in orbit radius of the geostationary ring. However, an inclination limit is not formally defined. While operational, COMSATs are usually controlled to maintain their orbit within ±0.1° of an allocated longitude position and to avoid significant drift north-south. Without active propulsion, i.e. around and after end-of-life, the inclination increases to about 15° due to the Sun's and Moon's gravitational pulls, but most satellites are boosted to a graveyard orbit at this stage which is typically 300 km or more above the geosynchronous ring.

The G-CLASS orbit inclination and eccentricity are defined so that the satellite remains outside a box 400 km in size radially and north-south. The satellite thus remains about 300 km away from the geostationary ring at all times (Fig. 1). The inclination and eccentricity must be phased correctly to achieve this: the resulting projection of the relative orbit on Earth's surface is an almost perfect diagonal line (Fig. 2). Such an orbit is good for imaging perpendicular to this line since the azimuth speed component is high, but viewed ‘end-on’ the apparent satellite speed is very low and integration times would be too long to form useful synthetic apertures. Table 3 lists orbital elements for the baseline G-CLASS

Table 1 Science Objectives

Label	Objective
SO1	improve the prediction capability for intense rainfall and related flooding and landslides.
SO2	improve understanding of the diurnal water cycle, especially soil moisture in dry environments and snow melt/re-freeze in mountain regions.
SO3	enable near real-time monitoring of ground motion (and response management) for landslides, earthquakes and volcanoes.

Table 2 Geophysical measurement requirements related to science objectives (IWV = Integrated Water Vapour, SM = Soil Moisture, SWE = Snow Water Equivalent)

Measurement requirement	Obj.
IWV: 0.5–1 km, 15 min, 1 kg $\mathrm{m^{-2}}$	SO1
SM, coarse: 1 km, 15 min, 0.05 $\mathrm{m^3\ m^{-3}}$	SO1
SM, fine; 200 m, 3 h, 0.02 $\mathrm{m^3\ m^{-3}}$	SO2, 3
snow extent: 100 m, 3 h	SO2
SWE: 100 m, 3 h, 5 mm	SO2
ground motion: 20 m, 6 h, 2 mm $\mathrm{day^{-1}}$	SO1, 3
flood extent: 30 m, 3 h	SO1, 3

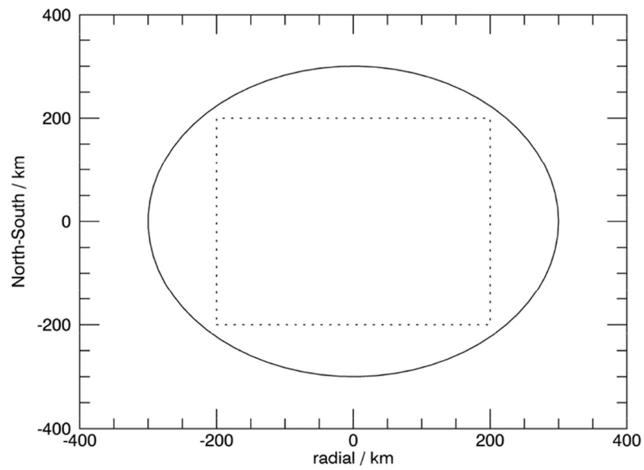

Fig. 1 *Projection of the G-CLASS orbit (solid line) in the radial/north-south plane showing how it remains outside a protected region (dotted line) 200 km around the geostationary ring; the satellite completes each orbit around the protected region in 1 sidereal day*

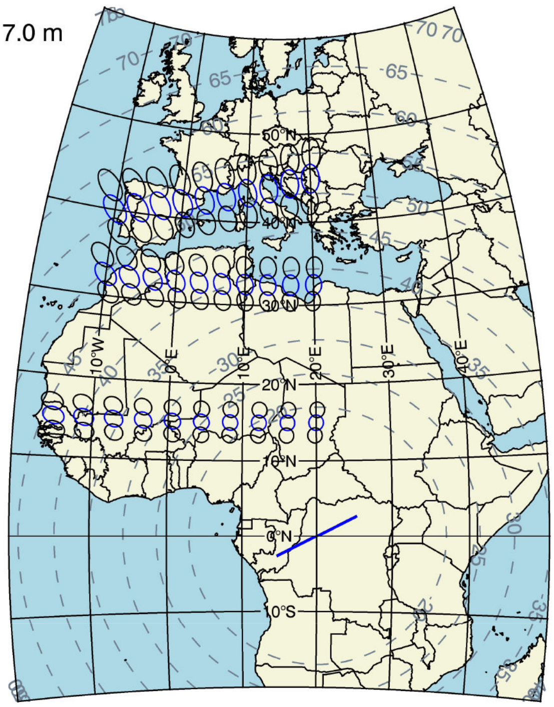

Fig. 2 *OHB Hispasat 38W-1: an example small GEO satellite compatible with the G-CLASS mission concept (OHB)*

orbit. The argument of perigee determines whether the orbit ground track is aligned south-west to north-east (0°) or south-east to north-west (180°). A user chooses combinations of Right Ascension (Ω) and perigee passage (t_p) to place the orbit mid-point at a chosen longitude and the satellite's position around the orbit at a given moment.

The maximum speed relative to Earth is just over 40 m s^{-1} (it varies sinusoidally with a period of 1 sidereal day). Typical speed is thus 20–40 m s^{-1}, and at C-band it takes 25–50 s to form an aperture 1 km long, which achieves a spatial resolution on Earth's surface of ∼1 km. Using the link budget for these integration times, typical radar designs use a transmitted RF power of around 400 W and an antenna diameter of 7–10 m. These values are feasible with current technology and are encouraging that G-CLASS provides a good compromise which achieves useful performance with a relatively conservative spacecraft design.

3 G-CLASS system design

System design flows from the science objectives and required payload performance.

3.1 Payload

As noted above, a feasible C-band radar payload design for the G-CLASS missions uses an antenna diameter of 7 m and transmitted RF power of 400 W. The most cost-effective antenna technology is to use an array of feed-horns illuminating a lightweight deployable reflector. This has been chosen for G-CLASS – an electronically steered phased array is more attractive technically but would make G-CLASS infeasible for the target budget defined by ESA's Earth Explorer 10 call. The payload requires about 1.5 kW of electrical power and thus is compatible with one of the small GEO satellites now available.

3.2 Beam steering

For G-CLASS to be useful, it must be able to steer its spot beams over regions of interest. This will be done by slewing the whole satellite (only a few degrees of slew are needed to steer the beams across Europe or Africa). Reaction wheels allow this to be done without additional fuel use. Dual or compact polarisation is assumed to give partial polarimetric imaging capability.

Table 3 Baseline orbit parameters for G-CLASS

Orbital element	Value
semi-major axis (a)	42 164 km
eccentricity (e = 300 km/a)	0.007115
inclination (i = 300 km/a)	7.115 mrad = 0.408°
argument of perigee (ω)	0 or 180°
right ascension of ascending node (Ω)	<USER choice>
time since perigee (t_p)	<USER choice>

Fig. 3 *Example G-CLASS spot beam coverage (C-band, 7 m diameter antenna; implemented with SPOT/TOPS imaging modes); the diagonal line shows the G-CLASS orbit projection on earth's surface, dashed lines show local incidence for an orbit centred at 20°E*

The communication link is straightforward since the satellite has a permanent link to its ground station, and the data bandwidth (100 Mbit s^{-1} or lower) is not especially demanding. Significant signal processing is needed on ground to focus the coarse and fine resolution images. The various effects (atmospheric phase variations, orbit drift, clock synchronisation) which need to be tracked and compensated for are the main technical risk for the mission [9].

3.3 Spacecraft Bus

All other sub-systems are relatively low-risk. The mission plan includes an end-of-life phase where its orbit will be circularised and then raised to leave it in the GEO graveyard region. The baseline design uses OHB's SmallGEO platform (in use for Hispasat 38W-1, Fig. 3), which is also available with electric propulsion. Using electric propulsion it is possible to raise the satellite orbit from low Earth orbit (where it may be delivered using small, low-cost launchers) to GEO in less than a year – and the electrical power needed for electric propulsion is also useful later in the mission for the radar payload.

3.4 G-CLASS evolution

A mission concept such as G-CLASS creates many options for evolving the mission. Additional satellites could provide extra geographical coverage (either 'locally', over the same regions, or globally) could enable advanced multi-static imaging modes, or provide complementary bands. Towards the end of its life, G-CLASS could transition to a receive-only function to provide passive radar, or may be able to continue imaging from its graveyard orbit. Each of these creates exciting future mission possibilities.

4 Discussion and conclusions

G-CLASS introduces another concept to the spectrum of GEO radar missions already proposed. It is shaped by the ESA Earth Explorer 10 mission opportunity for which it was designed (especially the science drivers, Vega-C launcher and mission budget), but introduces a new orbit option which is intermediate between the quasi-geostationary orbits already discussed especially by European groups, and the higher inclination orbits proposed by Chinese and US groups.

Some uncertainties remain concerning the G-CLASS mission design. The most important is probably its orbit design, especially its practical compatibility with commercial COMSAT operations and RF interference. These matters require deeper study if the mission concept is to progress.

Apart from this compatibility with commercial COMSATs, the remaining risks are to performance rather than fundamental feasibility. For example, deployable antennas are being developed, and although the performance is adequate with a 7 m diameter antenna, larger antennas improve performance and so a larger antenna should be used if available. There are technical risks related to the phase compensation, especially the atmospheric phase compensation. However, the algorithms already outlined (e.g. in [9]) are almost certain to work in benign conditions: the uncertainty is, therefore, primarily about the range of weather conditions in which phase compensation can be performed rather than its fundamental feasibility.

We believe that G-CLASS provides an exciting observation capability which could transform aspects of Earth science and open up new imaging opportunities from space. Its potential justifies further work on the G-CLASS mission concept, and for GEO radar more generally.

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